Defense Technical Information Center
Compilation Part Notice

ADP010989

TITLE: A Combination of Biomechanical and Physiological Approaches for Determination of Optimal Load Distribution

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Soldier Mobility: Innovations in Load Carriage System Design and Evaluation [la Mobilite du combattant: innovations dans la conception et l'evaluation des gilets d'intervention]

To order the complete compilation report, use: ADA394945

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP010987 thru ADP011009

A Combination of Biomechanical and Physiological Approaches for Determination of Optimal Load Distribution

A.X. Bigard

Médecin en Chef
Unité de Bioénergétique, Centre de Recherches du Service de Santé des Armées,
BP 87, 38702 La Tronche Cedex, France

Summary

France is developing an integrated soldier ensemble that will improve soldier protection, survivability and sustainability. Improvement of the soldier's load carrying capacity remains an important step that will contribute to the maintenance of good health and protection against the side effects induced by soldier systems. A number of factors can influence the energy cost associated with locomotion. The aim of many studies has been to determine the level of oxygen uptake that can be maintained without physical fatigue. A myriad of kinematic and kinetic parameters may directly or indirectly influence the energy cost of locomotion, especially when subjects are walking with loaded backpacks. While the metabolic energy cost of human movement is easy to estimate by the global measure of total body oxygen consumption (V_{O2}), a variety of computational techniques have been suggested as appropriate for the calculation of mechanical power. The changes in energy of the centre of mass (via ground reaction forces) have been frequently used to estimate the mechanical power of locomotion. One limitation of these measures is that they do not include the work done in moving the limbs and arms. This work, often termed "internal work", is one essential component of total mechanical work associated with locomotion. Because measures of mechanical power which do not include contributions from all of the internal and external work done may provide misleading information, recent methods involving a segmental analysis have been suggested to determine the changes in the energy of individual body segments. Thus, measures of both oxygen consumption during walking and load carriage, and mechanical work are two essential steps in the assessment of the relationship of physiological energy expenditure to mechanical factors. Our approach to the study of human movement efficiency involves determination of the mechanical efficiency of human locomotion with backpack loads simultaneously with measurement of biochemical, cardiovascular, muscular and mechanical responses that occur during treadmill walking. In the framework of the development of the French soldier system, the first step of our program is to determine the optimal distribution and placement of the load by examining the changes in mechanical work, muscular activity and energy cost of walking on a treadmill.

Introduction

Despite considerable modernization of military equipment, load carriage by backpack is still a requirement for soldier on the battlefield. The tolerance of load carriage is critical for soldier performance and prevention of side effects such as localized muscular discomfort and muscular injury leading to fatigue. Particular attention should be paid also to the maintenance of efficiency of locomotion during prolonged walking in order to prevent progressive shifts in the metabolic energy cost and in core temperature.

Efficiency of human movement

Efficiency of human movement is an important topic in exercise physiology. As for athletes, the efficiency of movement is a critical factor for the maintenance of a given task for soldiers. A number of factors can be identified which would be likely to have an influence on the efficiency of movement, among them biochemical, physiological, biomechanical and psychological factors. When one attempts to estimate the efficiency of human movement, the most common definition used is that set forth by Stainsby et al. (1980):

$$\frac{\text{mechanical} \quad \text{work}}{\text{energy} \quad \text{expended}}$$

While equations exist to predict the energy expended and the metabolic energy cost of locomotion, there is a great intersubject variation in the oxygen uptake at a given walking speed, under specific terrain conditions and with external loads. It is not possible to accurately attribute these individual variations in the energy cost of locomotion to particular factors known to contribute to the efficiency of human movement (Cavanagh and Kram, 1985). Although individuals vary considerably in the amount of energy expended to perform the same submaximal task, these differences in oxygen consumption (VO_2) cannot directly be interpreted as differences in efficiency. At a given walking speed, a high value of VO_2 may reflect a high mechanical work with similar values of muscular efficiency. Because it is not practical to measure true effectiveness in human subjects, it is thus clear that an integrated approach of the biomechanical and physiological characteristics of human locomotion appears very useful. This is the case for prolonged walking with external loads.

Physiological strain of walking with external loads

Because VO_2 for a given task has been emerged as a practical index for the evaluation of performance during endurance activity, an extensive amount of research has been conducted to study the energy expenditure during walking while carrying external loads. The general conclusions of these studies have been that the energy cost of walking is affected by the velocity, terrain factors such as grade and surface, the weight, size and shape of the load carried. Subsequently, mathematical prediction models of the energy cost of walking or running with graded loads have been developed, principally by the Natick's laboratory (Pandolf et al., 1977; Pimental and Pandolf, 1979).

One point deserves particular attention. In military operations soldiers are required to cover long distances and the majority of studies dealing with determination of the energy cost of walking with external loads considered tasks of relatively short duration. One important question concerns the effects of load carriage on the economy and/or muscular efficiency of prolonged walking over several hours.

Many previous studies demonstrated a gradual increase in VO_2 during prolonged activities such as walking, running or bicycle exercise. Epstein et al. (1988) showed for the first time an increase in the energy cost of walking over time while carrying external loads. Results of this study showed that carrying 25 kg (37 % of body weight) did not significantly affect the oxygen uptake expressed per kg body weight and external load while subjects walk at a constant speed of 1.25 m/s. However, carrying a heavy load, the energy cost per kg increased significantly over time in a linear fashion (Figure 1).
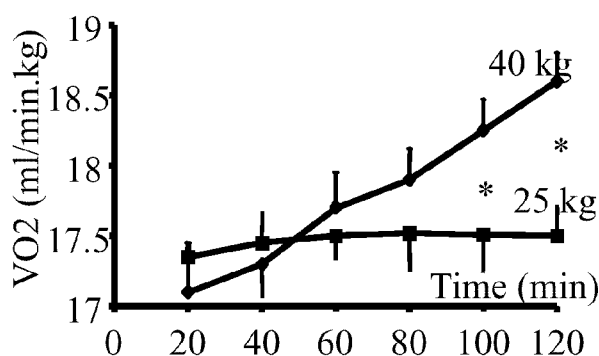

Figure 1. Effects of load carriage on oxygen uptake, expressed per kilogram of body weight+external load. (Epstein et al., 1988)

In accordance with these results, a progressive rise in VO_2 has been observed during a 12 km walk with heavy load carriage (Patton et al., 1991). In this study, it was interesting to note that VO_2 was found to increase over time for exercises as low as 27% of VO_2max. Several mechanisms may be responsible for the rise in the metabolic energy cost of walking, but it is very likely that altered biomechanics plays a key role in the decrease in walking economy. To our knowledge, this aspect has not been extensively studied and it would be interesting to examine the relationship between mechanical and physiological energy estimates during prolonged walking with external load.

For this purpose, we need estimates of metabolic energy cost and mechanical work of locomotion. The measure of oxygen consumption is generally accepted as a convenient method of assessing the metabolic energy cost of prolonged activity. However, the main problem is to have an accurate measure of the mechanical work done by the muscles in walking or running.

Mechanical work estimates during walking with external loads

The total mechanical work has been partitioned into the internal work due to the speed changes of body segments with respect to the body center of mass and the external work related to the position and speed changes of the center of mass in the environment:

Internal work
Eb(t) = Σ poE(i,t) + Σ trKinE(i,t) + Σ rotKinE(i,t)
Wi = Σ ΔEi
External work
We = Wpo + Wkin
= mg(Hmax-Hmin) + 0.5m(V^2max-V^2min)

where Wi is the internal work, poE(i,t) is the potential energy of the *i*th body segment at time *t*, trKin is the translationial kinetic energy of the *i*th body segment at time *t*, rotKin is the rotational kinetic energy of the *i*th body segment at time *t*; We is the external work, Wpo is the positive work against gravity, and Wkin is the positive work necessary to accelerate forward the center of mass during each step.

External mechanical work is frequently calculated from the total energy changes of the center of mass of the body, while internal work results from the summation of potential, translational kinetic and rotational kinetic energy components of all body segments. A number of authors have used a point mass model of the body to calculate the external mechanical work. The external work can be obtained from ground reaction forces. The total body energy as calculated from the center of mass energy is lower than the sum of segments energies, with average error varying between 16.2 to 40% (Winter, 1979). This apparent discrepancy is partly due to energy changes in reciprocal movements.

Force platforms are frequently used to measure ground reaction forces in order to calculate external mechanical work. Using this method, it has been previously shown that the mechanical work increased with increasing external load (Figure 2) (Pierrynowski et al., 1981). This finding was clearly expected but an interesting result was that mechanical work raised more slowly than metabolic cost.

One limitation of such a study is that all measurements have been done after only twelve minutes of walking. More marked alterations of mechanical work are expected after long term load carriage. An additional problem using force platform during walking, is the short measurement distance making it difficult to obtain constant velocity. Moreover, only few data are collected and the variability and asymmetry of dynamic step parameters can not be fully taken into account.
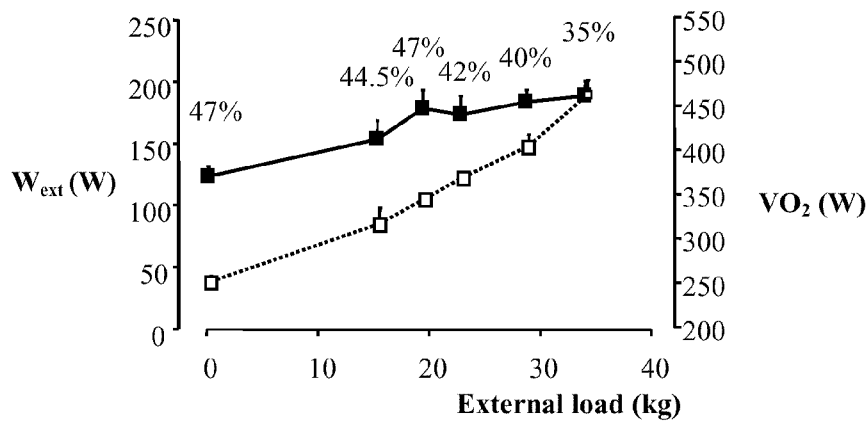
Figure 2. Changes in mechanical ▬■▬, and metabolic ··☐··
work rates with increasing external load et al., Pierrynowski et al., 1981)

On the other hand, one major limitation of such a approach evaluating mechanical work from the energy changes of the center of mass is that internal work can not be measured by means of force plate data. The main source of internal work is the kinetic energy changes of the limbs calculated from their velocity relative to the center of gravity. In theory, internal work can be estimated by motion analysis, but there are two major limitations of this approach. First, segmental energy increase may result from muscular contraction, transfer of energy between segments and/or elastic storage and return of energy, but there are great interindividual differences in the ability to store elastic energy under locomotor conditions. Energy can be stored in elastic tissues of the musculoskeletal system and subsequently contribute to the positive work. If elastic contributions are thought to be minimal in normal walking, it is likely that walking with external loads represents a favorable situation for elastic storage and return.

Secondly, many previous works demonstrated that the amount of energy expended differs for concentric and eccentric contractions (Williams, 1985). Thus, it would be incorrect to simply add the absolute values of the negative and positive changes in mechanical energy. Suggestions have been made to add to positive work only a portion of the calculated negative work, as exemplified by the following equation:

$$Mech(tot) = Mech(+) + [Mech(-)/d]$$

Where Mech(tot), Mech(+), Mech(-) are the total, positive and negative mechanical works, respectively, and d is the efficiency of negative to positive muscular power. However, the d value could range from 2 to 6 (Williams, 1979). In conclusion, there is no valid measurements of total mechanical work of muscles during walking.

Although valid measurements of total mechanical work, including both external and internal work cannot be achieved, the effects of carrying loads on selected kinematic and kinetic parameters of walking gait is of great interest. Previous studies showed that the energy cost of running was associated with specific running pattern (Williams and Cavanagh, 1983). More interesting, we have previously shown that the energy cost of running increases over time. This increase in the energy cost observed at the end of a marathon or a triathlon is associated with an alteration of selected kinematic parameters (Hausswirth et al., 1997). These findings demonstrate that selected temporal and kinematic parameters could provide interesting information on the effects of load carriage on walking gait over time.

A pioneer study showed that the magnitude of the carried load only slightly affected the stride length in men (Martin and Nelson, 1986). Swing time and double-support time also showed little changes as the load was increased. Taken together, these results showed that the changes in global gait characteristics with load carriage were only small. However, one major problem with this study is that measurements were done after only short periods of walking. Moreover, when walking speed was not freely chosen but maintained constant, double and single support periods lengthened significantly as the load increased (Kinoshita, 1985).

The results of this latter study suggested that light external loads as light as 20% of body weight are liable to alter the pattern of gait of subjects not acclimatized to carrying activities.

Kinematic analysis of body segments and joint angles revealed that load carriage was associated with a greater knee flexion during the loading phase (Kinoshita, 1985). This finding has been explained as an adjustment of knee joint in order to function as a shock absorber to reduce the impact force. All these data suggest that gait characteristics are only slightly affected by load carriage. However, once again, motion analysis has been performed after short period of walking. But whether prolonged walking with heavy loads affects the energy cost of locomotion and alters the walking gait remains to be clearly determined.
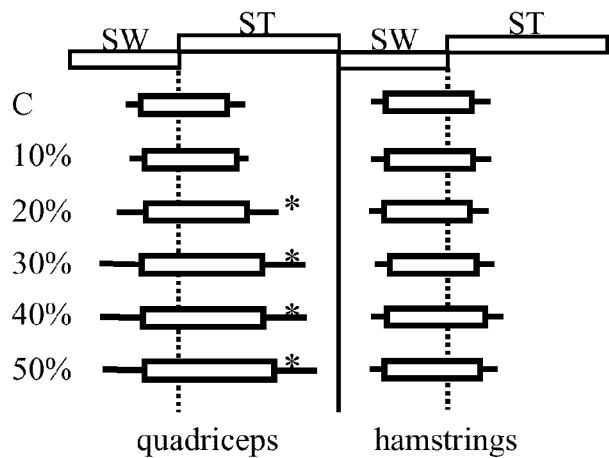

Figure 3. Activity patterns of two lower limb muscles
in control walking (C) and when carrying external loads. SW,
swing phase of the step cycle; ST, stance phase of the step cycle.
*, significantly different from C.
(from Ghori and Luckwill, 1985)

External load distribution

Many previous studies showed that heavy loads should be kept as close as possible to the trunk and center of gravity of the body in order to minimize fatigue and local muscle discomfort. Less known is the physiological cost of various modes of carrying a load close to the trunk. A previous study failed to show any significant difference between five modes of load carriage for several physiological parameters after one hour of walking (Figure 4) (Legg and Mahanty, 1985). However, carrying the load using a trunk jacket or half of the load in a standard backpack and the other half in a front pack was subjectively rated as more comfortable. Taken together, these results suggested that it is difficult to assess the optimum mode of load carriage only by physiological measurements such as oxygen consumption or heart rate.
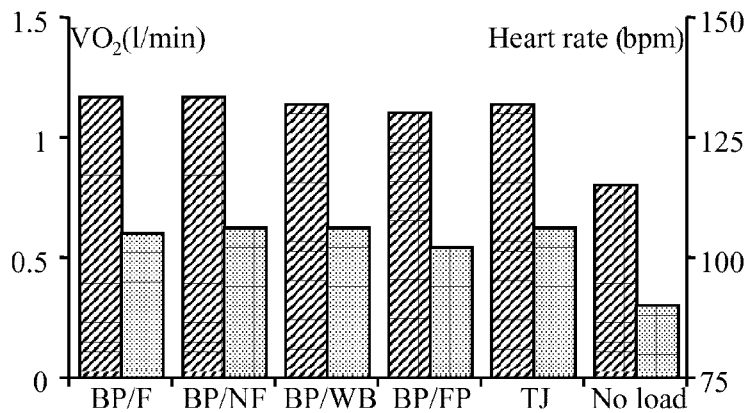
Figure 4 :Effects of five modes of carrying a load close to the trunk on oxygen uptake (VO₂) and heart rate . BP/F, backpack with frame; BP/NF, backpack with no frame BP/WB, backpack with waist belt; BP/FP, backpack with frontpack; TJ, trunk jacket.
(Legg and Mahanty, 1985)

The acute effects of both light and heavy loads by means of two different carrying systems on some kinematic parameters of walking gait have been evaluated (Kinoshita, 1985). Step with and total support values while carrying loads using a double-pack system were more similar to those of normal walking with no load than for the backpack condition. The backpack system caused much greater forward inclination of the trunk and thigh than with the doublepack system. It was concluded that the doublepack system prevented the marked forward lean of the trunk expected while carrying heavy loads. The results of this study showed that the doublepack system was biomechanically more effective for carrying loads and that normal gait patterns were less affected when subjects used this carrying device than when they used a conventional backpack system.

Conclusion

In conclusion, the purpose of this paper was to discuss the methods used to evaluate the tolerance of load carriage systems. Load carriage systems are critical to soldier performance on the field and health, and thus an improved methodology is need in order to determine the suitability of a mode of load carriage. The experimental approach should determine the responses of several components to a backpack design, such as physiological (i.e. oxygen consumption and muscle activity measurements), biomechanical parameters (i.e. measures of ground reaction forces and selected kinematic characteristics of walking) and subjective measurements of discomfort. These measures should be compared to selective task performances as essential in military operations.

References

Cavanagh, P.R., and R. Kram. The efficiency of human movement – a statement of the problem. *Med. Sci. Sports Exerc.* 17: 304-308, 1985

Epstein, Y., J. Rosenblum, R. Burstein, and M.N. Sawka. External load can alter the energy cost of prolonged exercise. *Eur. J. Appl. Physiol.* 57: 243-247, 1988

Ghori, G.M.U., and R.G. Luckwill. Responses of the lower limb to load carrying in walking man. *Eur. J. Appl. Physiol.* 54: 145-150, 1985

Hausswirth, C., AX. Bigard, and CY. Guezennec. Relationship between running mechanics and energy cost of running at the end of a triathlon and a marathon. *Int. J. Sport Med.* 18 : 330-339, 1997

Kinoshita, H. Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait. *Ergonomics.* 28: 1347-1362, 1985

Legg, S.J., and A. Mahanty. Comparison of five modes of carrying a load close to the trunk. *Ergonomics.* 28: 1653-1660, 1985

Martin, P.E., and R.C. Nelson. The effect of carried loads on the walking patterns of men and women. *Ergonomics.* 29: 1191-1191, 1986

Pandolf, K.B., B. Givoni, and R.F. Goldman. Predicting energy expenditure with loads while standing or walking very slowly. *J. Appl. Physiol.* 43: 577-581, 1977

Patton, J.F., J. Kaszuba, R.P. Mello, and K.L. Reynolds. Physiological responses to prolonged treadmill walking with external loads. *Eur. J. Appl. Physiol.* 63: 89-93, 1991

Pierrynowski, M.R., R.W. Norman, and D.A. Winter. Mechanical energy analyses of the human during load carriage on a treadmill. *Ergonomics.* 24: 1-14, 1981

Pimental, N.A., and K.B. Pandolf. Energy expenditure while standing or walking slowly uphill or downhill with loads. *Ergonomics.* 22: 963-973, 1979

Stainsby, W.N., L.B. Gladden, J.K. Barclay, and B.A. Wilson. Exercise efficiency: validity of base-line substractions. *J. Appl. Physiol.* 48: 518-522, 1980

Williams, K.R. The relationship between mechanical and physiological energy estimates. *Med. Sci. Sports Exerc.* 17: 317-325, 1985

Williams, K.R., and P.R. Cavanagh. A model for the calculation of mechanical power during distance running. *J. Biomech.* 16: 115-128, 1983

Winter, D.A. A new definition of mechanical work done in human movement. *J. Appl. Physiol.* 46: 79-83, 1979

This page has been deliberately left blank

———————————

Page intentionnellement blanche